Simulation studies on electrical characteristics of conical and pyramidal field emitters

Fu Jianyu[1,2], Chen Dapeng[2], Wang Guoyin[1], Wu Di[1]

(1. Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing 401122, China;
2. Integrated Circuit Advanced Process Center, Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China)

Abstract: Conical and pyramidal emitters are two generic field-emitter structures. Due to specific advantages of field emission, both emitters are widely employed to produce electron beams. The main focus of this paper is to analyze the electrical characteristics of both emitters, and further, to highlight the key criteria in optimizing the structures. For this purpose, three-dimensional models were implemented and finite-element analysis was used to investigate the influences of emitter geometries, including shape of emitter, emitter radius of curvature, emitter-anode distance and emitter height, on its electric field distribution and strength. The results indicate that reducing tip radius of curvature and shorting the emitter-anode distance are effective ways to increase the field strength enhancement, while a proper ratio of the emitter height to the emitter-anode distance is also an important factor. In addition, in consideration of both electric field distribution and strength, the conical emitter is suitable for high-resolution, large current-density applications, whereas the pyramidal emitter has better pressure sensitivity.

Key words: field emission; simulation; vacuum electric devices

CLC number: O462.4 **Document code:** A **Article ID:** 1007-2276(2014)07-2277-06

锥形与金字塔形场发射尖端电学特性分析

傅剑宇[1,2],陈大鹏[2],王国胤[1],吴 迪[1]

(1. 中国科学院重庆绿色智能技术研究院,重庆 401122;
2. 中国科学院微电子研究所 先导工艺研发中心,北京 100029)

摘 要: 场致电子发射具有高效、响应快等优点,有着广泛的应用前景。锥形和金字塔形尖端是两种常见的场发射尖端结构。主要分析了这两种尖端结构的场发射电学特性,并在此基础上提出了进一步实现结构优化的途径。为此,建立了两种尖端的三维模型,并利用有限元法深入讨论了结构尺寸,包括尖端曲率半径、尖端与阳极间距以及尖端高度对电场分布以及电场强度的影响。结果表明,减小尖端曲率半径、缩短尖端与阳极间距、以及选择适当的锥体高度是优化尖端场致电子发射性能的三个重要途径。在综合考虑电场分布以及电场强度的情况下,可以发现锥形尖端更有利于产生高密度小束径的低能电子束,而金字塔形尖端则更适用于高压力灵敏度的应用需求。

关键词: 场发射; 仿真; 真空电子器件

收稿日期: 2013-11-14; **修订日期:** 2013-12-19

基金项目: 重庆市科技攻关计划(CSTC2011GGC40008);中国科学院西部之光人才项目

作者简介: 傅剑宇(1984-),女,博士,主要从事微机电系统方面的研究。Email:fujianyu@cigit.ac.cn

0 Introduction

Vacuum microelectronic technology is becoming increasingly important in research and everyday life[1]. The relatively fast response, wide temperature operation, and low power consumption of field emission makes the field emitter an ideal electron source, and a potentially useful structure for numerous applications[2-5]. These devices based on field emission are typically made by micromachining techniques[4-7]. Two generic emitter structures are obtained: conical and pyramidal structures. Some simulations on field emitters, with the intention to enhance electron emission characteristics, have been reported[8-11]. While most of them were concerned with conical emitter[8-10], the works mentioning two emitters mainly focused on the influences of tip radius[11]. Considering the geometric design parameters not only are essential to device design, but also greatly affect field emission; it is important to discuss the effects of practical variations in geometry on electrical characteristics of conical and pyramidal emitters. In this article, the 3D models of two emitters are firstly generated based on their structures. The simulations are then performed. From the analysis, emphasis has been put on understanding the difference of the electric field distribution and the effects of emitter geometries on the electric field strength between these two emitters, and the optimization of each emitter was also discussed.

1 Emitter models

The field-emission simulations were carried out in the models shown in Fig.1. The main geometric design parameters being considered in our models are the emitter radius of curvature r, emitter-anode distance d, and emitter height h. For the simulations, the conical emitter was considered as an isotropic profile and its tip was approximated by a hemisphere; the half-angle θ of the pyramidal emitter was set to 54.7°, which is the result of anisotropic etching of silicon.

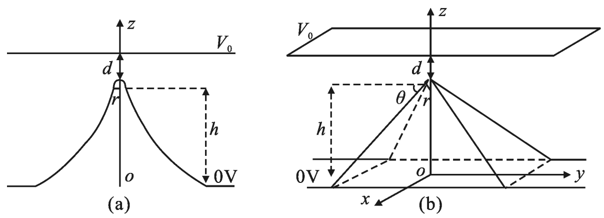

Fig.1 Models of conical emitter and pyramidal emitter

The vacuum region between the anode and emitter is meshed by 3-D 10-node tetrahedral electrostatic element, and a high density of mesh elements is introduced near the tips to achieve suitable credibility, as shown in Fig.2.

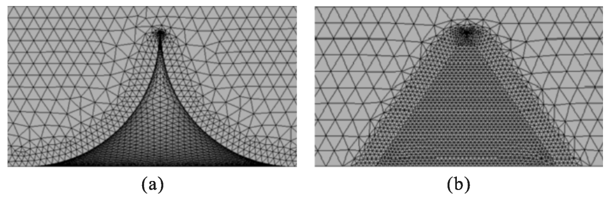

Fig.2 Mesh of the vacuum region between the anode and conical emitter, pyramidal emitter

If we neglect the space-charge effect in the vacuum region between the anode and emitter, the potential obeys the Laplace equation:

$$\nabla^2 V=0 \tag{1}$$

$$V|n=V_f \tag{2}$$

Where V is the electric potential, n denotes the boundary, and V_f is the boundary value.

Once the potential and field strength are obtained, the current density of field emission can be calculated according to the Fowler-Nordheim equation[12]:

$$J(E)=\frac{AE^2}{\phi t^2(y)}\exp\left(\frac{B\phi^{\frac{3}{2}}v(y)}{E}\right) \tag{3}$$

Where E is the electric field strength, ϕ is the work function, and $y=3.79\times10^{-4}E^{\frac{1}{2}}\phi^{-1}$, $A=1.54\times10^{-6}$, $B=6.86\times10^7$, $t^2(y)\approx1.1$, and $v(y)=0.95-y^2$.

2 Simulation results and discussion

Numerical simu lations were carried out as variables of r, d, and h. The emphasis of our investigation is to compare the difference between these two emitters and to identify the structural parameters that possibly enhance the electric field strength.

2.1 Electric field distribution

Regarding the simulations of field emitters, r is 40 nm, d is 1 μm, h is 5 μm, and V_0 is 100 V. The results of the electric field distribution are shown in Fig.3. It can be seen that the electric field strength at the tip of both emitters is sharply increased. This can be attributed to the tip effect. As demonstrated in Fig.4, the equipotential lines in the vacuum space of both emitters are obviously concentrated over the tip top, and the relative spatial electric field strength can be determined by differentiating the potential. As a result, the strongest electric field strength occurs at the tip top of the field emitters. In addition, it can be also seen from Fig.3 that the electric field distribution of the pyramidal emitter is not the same as that of the conical emitter. This may be caused by the difference of structure geometry of field emitters. The pyramidal emitter has four wedges along its height, and the neighboring potential is strongly affected by this geometry. The electric field strength was highly localized at the wedges, but also, the maximum electric field strength at the tip became lower than that in the conical case as a result of wedge field influence.

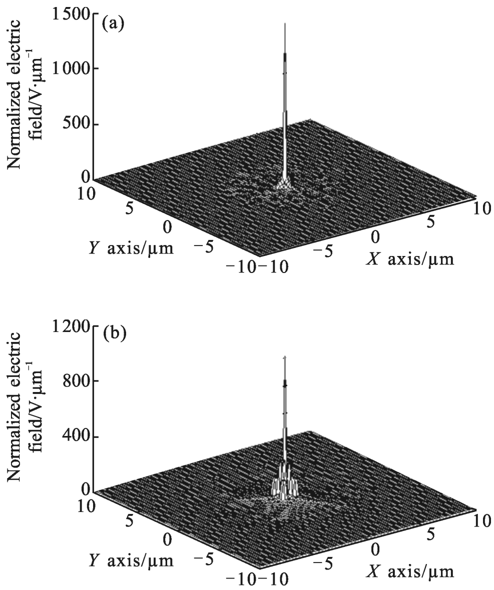

Fig.3 Spatial electric field distribution of conical emitter and pyramidal emitter with r=40 nm, h=5 μm, d=1 μm, V_0=100 V

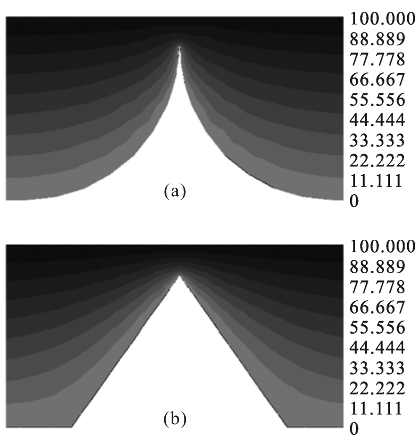

Fig.4 Profile of equipotential lines of conical emitter and pyramidal emitter

The effective emitter area will increase with higher applied voltage, and if the applied voltage is high enough, the wedges of the pyramidal emitter will contribute to the electric emission, so that the effective emission area will be greatly increased. Therefore, it is clear that the conical emitter is more suitable for some field-emission applications that require precision, such as flat-panel displays and nanolithography, because the emitters for these applications must have small beam size and high current density.

2.2 Electric field strength

2.2.1 Dependence on emitter radius of curvature r

Simulations were performed on the case of h=5 μm, d=1 μm, V_0=100 V, and r varying from 0.01 to 0.1 μm. The simulation results are shown in Fig.5. For both emitters, the electric field strength at the tip is increased as r reduces. And the field strength follows a functional form that approximates $e^{-\frac{r}{\alpha}}$, where α depends on the structure parameters. This result is in good agreement with the earlier simulations of Mologni et al[11]. This phenomenon can be easily understood by the fact that the sharper the tip, the denser the equipotential lines over the tip, and hence, the stronger the field strength. For comparison, a tip electric field strength plot with 200 V of applied voltage is also shown in Fig.5. It is obvious that the variation trend of the field strength with r is independent of applied voltage, although the field strength is increased compared to the case with 100 V.

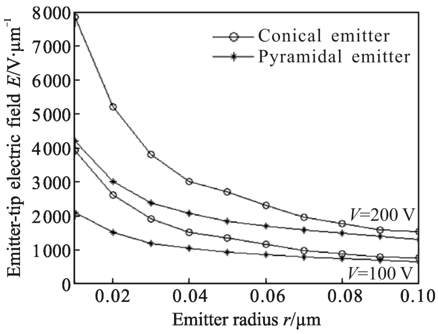

Fig.5 Effect of tip radius of curvature on the tip electric field strength for conical and pyramidal emitters with h=5 μm, d=1 μm

2.2.2 Dependence on emitter-anode distance d

Considering the emitters with parameters of h= 5 μm, r=40 nm, V_0=100 V, and d varying from 0.04 to 8 μm, simulations were carried out, and the results are shown in Fig.6. For the case of $d>>r$, only a small increment of the electric field strength E is observed for both emitters with shortening the d, which implies that r is the main factor that affects field strength. As d reduces, r and d become comparable. The effect of d on E begins to appear for both emitters, and the slope of the E-d plots becomes abrupt. This is because the equipotential lines become much denser between the anode and tip top of emitters as d is greatly shortened. Therefore, E over the tip top is enhanced. For the case of $d<<r$, the arc tip of the emitters with small d looks more like a plate rather than a tip, which makes both emitters behave like parallel-plate capacitors. As a result, E of both emitters tends to become close to each other when d is sufficiently reduced. Obviously, d instead of r becomes the main factor that then affects E. A much more general change trend of E with d is shown in Fig.7, where the variable of d is replaced by d/r. An interesting result is obtained, where the critical value of d causing obvious enhancement in E is about 10 times larger than r, i.e., d/r ~10. This value is independent of the emitter shape and radius of curvature for both emitters.

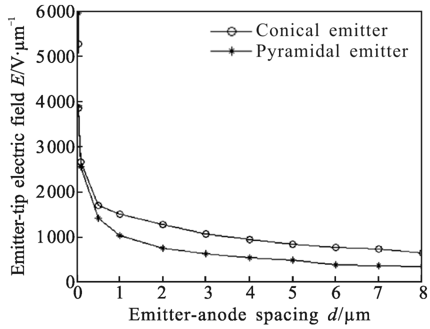

Fig.6 Effect of emitter-anode distance on the tip electric field strength for conical and pyramidal emitters with h=5 μm, r=40 nm, V_0=100 V

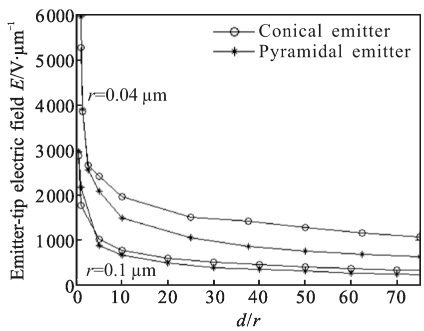

Fig.7 Tip electric field strength vs d/r plots for conical and pyramidal emitters with h=5 μm, V_0=100 V

As mentioned above, there exists an interaction between the wedge field and tip top field for the pyramidal emitter. With the decrease of d, this interaction is weakened because the field at the tip top is more localized. Thus, it can be said that the increase in E of the pyramidal emitter with small d is not only due to the decreased electrode spacing, but also to the weakened crosstalk of the wedge field. A small difference of E can result in a large current density difference because of the exponential characteristic of the Fowler-Nordheim relationship. Therefore, the pyramidal emitter has a stronger emitter-anode distance dependence of the tip top field than that of the conical emitter.

A potential application of field emission is in pressure sensors, which must have high sensitivity. Based on the above simulation result, an appropriate initialization of emitter-anode distance seems to be an important factor for improving the performance of pressure sensors, and the pyramidal emitter is an optimal choice for sensor applications with high sensitivity.

2.2.3 Dependence on emitter height *h*

The height of field emitters can be modulated in several ways, such as deposition method, oxidation condition, and etching control. Simulations were made to evaluate the effect of emitter height on electric field strength by using the same structure mentioned above. In this case, the parameters of emitter radius of curvature, emitter-anode distance, and applied voltage were kept constant(r=40 nm, d=1 μm, V_0=100 V), and the emitter height was varied from 0.5 to 7 μm.

As shown in Fig.8, the increase in the emitter height does not result in an obvious increase in field strength of both emitters when the emitter height h is larger than the emitter-anode distance d, i.e., 1 μm.

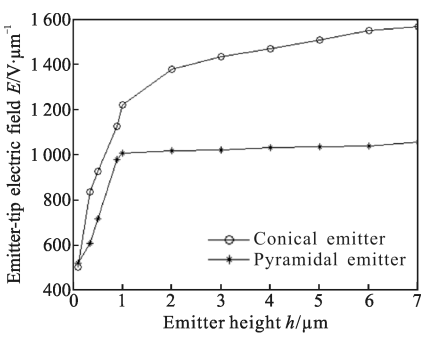

Fig.8 Effect of emitter height on the tip electric field strength for conical and pyramidal emitters with r=40 nm, d=1 μm, V_0=100 V

For example, as the ratio of h/d is enlarged from 1 to 7, the increment of the field strength is only 28% and 4.8% for the conical emitter and pyramidal emitter, respectively. When the ratio of h/d falls below 1, the field strength of the conical and pyramidal emitters decreases steeply with the decrease in h. Furthermore, as h becomes short enough, the field strength is independent of the emitter shape. This result may be due to the effect of a very uniform distribution of the vacuum potential. As shown in Fig.9, the vacuum potential is less disturbed by the short emitter compared to the high ones. A relative uniform potential distribution is observed for the short emitter, and the equipotential lines are much closer to those of parallel-plate capacitors. Thus, the tip effect is evidently weakened.

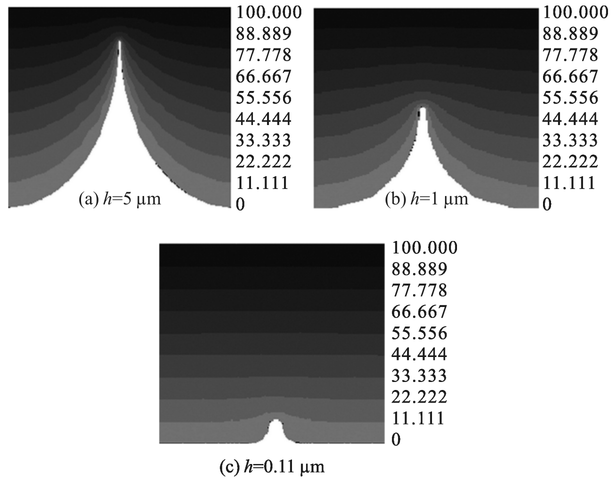

Fig.9 Equipotential lines of conical emitter where r=40 nm, d=1 μm, V_0=100 V

Figure10 shows a better field strength comparison of conical and pyramidal emitters. In this plot, the strength difference of two emitters is evident and the curved surface displays the relationship between the structural geometries and the electric field strength. Obviously, reducing tip radius of curvature, shorting the emitter-anode distance, and increasing emitter height will all increase strength increments; however, the optimization emitter parameters should also consider the technological factors.

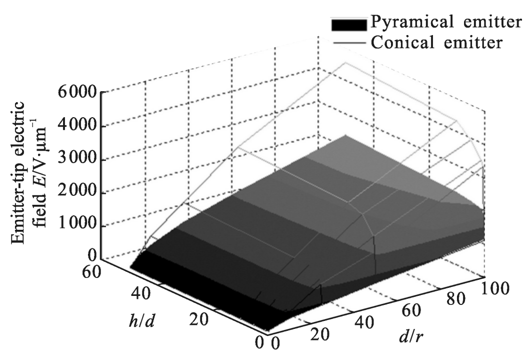

Fig.10 Electric field strength of conical and pyramidal emitters with various geometries for 100 V bias

3 Conclusion

In this paper, three-dimensional finite-element analysis is performed on both conical and pyramidal emitters. Simulation results reveal that the electric field strength of both emitters shows a great dependence on the structure parameters. There are two effective ways to increase the field strength, i.e., reducing tip radius of curvature r and shorting the emitter-anode distance d. For the case of $d/r>10$, the main effect on the field strength is r, whereas d becomes the dominant factor when $d/r<10$. In addition, a proper ratio of the emitter height to the emitter-anode distance($h>d$) is also important for field strength enhancement. The wedge field influence of the pyramidal emitter makes it has weaker field strength than that of the conical emitter, so conical emitter is more suitable for higher-resolution application. The field-strength variation rate with respect to the emitter-anode distance for the pyramidal emitter is higher than that of the conical emitter when $d/r<10$, indicating a potential application of pyramidal emitters for sensors due to its better pressure sensitivity.

References:

[1] Utsumi T. Vacuum microelectronics: what's new and exciting [J]. ***IEEE Trans Electron Devices***, 1991, 38: 2276-2283.

[2] Bishop H E. Electron emitters for flat panel displays [C]// 22nd Int Symp on Discharges and Electrical Insulation in Vacuum, 2006: 837-840.

[3] Luo H B, Shi Z L. Status and prospect of infrared imaging guidance technology [J]. ***Infrared and Laser Engineering***, 2009, 38(4): 565-573. (in Chinese)

[4] Zhang L, Tian Y, Li Q. Research status and prospect of dynamic infrared scene projector [J]. ***Infrared and Laser Engineering***, 2012, 41(6): 1421-1431. (in Chinese)

[5] Wen W, Wang L, Gao J, et al. Studies on MEMS vacuum sensor based on field emission of silicon tips array [C]// Proceedings of the 2nd IEEE International Conference on Nano/ Micro Engineered and Molecular Systems, 2007: 199-202.

[6] Busta H H, Shadduck R R, Orvis W J. Field emission from tungsten-clad silicon pyramids [J]. ***IEEE Trans Electron Devices***, 1989, 36: 2679-2685.

[7] Orvis W J, Mcconaghy C F, Ciarlo D R, et al. Modeling and fabricating micro-cavity integrated vacuum tubes [J]. ***IEEE Trans Electron Devices***, 1989, 36: 2651-2658.

[8] Mayer T M, Adams D P, Marder B M. Field emission characteristics of the scanning tunneling microscope for nanolithography [J]. ***J Vac Sci Techol B***, 1996, 14: 2438-2444.

[9] Seidl A, Takai M, Hosono A, et al. Geometry effects arising from anodization of field emitters [J]. ***J Vac Sci Techol B***, 2000, 18: 929-932.

[10] Marcus R B, Chin K K, Yuan Y, et al. Simulation and design of field emitters [J]. ***IEEE Trans Electron Devices***, 1990, 37: 1545-1550.

[11] Mologni J F, Alves M A R, Braga E S. Numerical study on performance of pyramidal and conical isotropic etched single emitters[J]. ***Microelectron J***, 2006, 37: 152-157.

[12] Beukema G P. Conditioning of a vacuum gap by sparks and ion bombardment[J]. ***Physica***, 1971, 61: 259-274.